OPERATIONAL SCENARIOS FOR MOBILE ROUTERS IN SPACE RADIATION ENVIRONMENTS

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Abstract

Several operational scenarios are identified for using commercial mobile router technology in space applications. Utilization of commercial products in space requires an understanding of the radiation environment and its interaction with matter. This is a reference when assessing the performance of hardware in space. Accurate numerical models provide the base for the body of knowledge study of the radiation effects on commercial mobile routers.

INTRODUCTION

NASA Glenn Research Center is currently involved in defining next-generation communication architectures for space. These architectures are attempting to utilize Internet Protocols to ensure interoperability between terrestrial and space based systems. Current research efforts are examining the use of mobile networking devices to support Internet Protocols in future space networks[1]. One such device is a commercial-off-the-shelf (COTS) mobile router, which includes hardware and software to support conventional network routing, and software to support network mobility. To be fully successful in space, COTS mobile router hardware and software will require rigorous analysis and testing to determine if the device can be used or modified for use in extreme space environments.

Mobile router technology offers the potential for transparent end-to-end connectivity with standardized protocols. However, this capability comes at the expense of more complicated software that may be difficult to certify for space flight use. The demands for software verification and validation of space rated systems will likely limit the use of many COTS products in space application. Determining the feasibility for qualifying mobile router software is an area for future research and not included within the scope of this investigation. For the purposes of this analysis, only hardware considerations are evaluated. Although to be fully realizable in space applications, software qualification issues must be addressed.

Electronics employed during space missions must be able to operate in the radiation environment for the duration of the mission. The two mechanisms by which radiation can create damage in electronics are ionization and atomic displacement. Ionization is caused by the collision of charged particles with matter. The charged particle passing through the medium may lose some or all of its kinetic energy. Atomic displacement is damage that results when high energy particles displace atoms from their usual site within the medium.

This investigation derives numerical models for several mission scenarios for the mobile router technology. The scenarios derived are: low earth orbit (LEO); ISS orbit (external to the craft); ISS orbit (internal to the craft); and lunar orbit. This report will present data on the environment for each scenario. This data will be used to help predict the damage that can be caused by ionization and atomic displacement.

The energy imparted by the ionization process is most commonly referred to as Total Ionizing Dose (TID). The TID accumulated by hardware is a function of orbit, shielding, and time.

Damage caused by atomic displacement is referred to as a Single Event Effect (SEE.) The SEE's experienced on orbit are not substantially mitigated by shielding because of the high energy of the particles producing the effect. The two major contributors to SEE's are the trapped protons in the South Atlantic Anomaly (SAA) and heavy ions due to Galactic and Solar Cosmic Rays.

This report provides background into the sources of radiation and some of the tools available to help model and analyze the effects radiation has on electronics and other hardware.

DEFINITIONS

absorbed dose – the absorbed dose (D) is the quotient of ΔE_D by Δm, where ΔE_D is the energy imparted by ionizing radiation to the matter in a volume element and Δm is the mass of matter in the volume element.
apoapsis – the point in an orbit farthest from the body being orbited

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apogee – the apoapsis in Earth orbit; the point in its orbit where a satellite is at the greatest distance from the Earth.

fluence – the time integrated flux.

functional interrupt (FI) – an event requiring a software reboot or a power cycle.

integral flux – at a given point, the number of protons or particles or energy incident per unit time on an area at that point, divided by the cross-sectional area.

ionization – the separation of a normally electrically neutral atom or molecule into electrically charged components.

ionizing radiation – any radiation consisting of directly or indirectly ionizing particles or a mixture of both.

linear energy transfer (LET) – generally described as: $L_\Delta = \left(\dfrac{dE}{dl} \right)_\Delta$ where dE is the energy lost in traversing distance dl and Δ is an upper bound on the energy transferred in any single collision.

periapsis – the point in as orbit closest to the body being orbited.

perigee - periapsis in Earth orbit; the point in its orbit where a satellite is nearest to the Earth.

single event burnout (SEB) – an event where the device has an abnormal conduction path established by the ionizing radiation and is destroyed almost immediately.

Single event effect (SEE) - an event caused by atomic displacement that results in permanent or temporary damage in a device.

single event latchup (SEL) – an event where the device has an abnormal conduction path established by the ionizing radiation and as indicated by a primary power supply current change. Power must be recycled to regain control and/or to save the device from destruction.

single event upset (SEU) – an event like a bit flip resulting in a data error only.

total ionizing dose (TID) - the total dose absorbed by a device over its operational life.

MOBILE ROUTER USE SCENARIOS

Scenario 1 – Polar Orbit Science Satellite

A mobile router onboard a science satellite could serve several purposes. First, the device could act as a gateway to isolate and rate limit data traffic between various onboard subsystems, such as command and data handling, attitude control, data storage, sensor data acquisition, and external communications interfaces[2]. In addition, the device could use mobility aspects in software to maintain end-to-end connectivity to a single ground processing site through a disperse ground station network. The operating environment would be an un-pressurized volume requiring an active or passive thermal control system.

Scenario 2 – International Space Station (external)

NASA Glenn Research Center has investigated concept architectures for a direct to ground communications system for the to augment the downlink of International Space Station science payload data (the Advanced Communications Architecture Demonstration). This system would be located on an external pallet adapter location. Similar to scenario 1, a router device could be used to isolate and rate limit subsystem communications as well as provided end-to-end connectivity to disperse ground stations. The operating environment would be an un-pressurized volume requiring an active or passive thermal control system.

Scenario 3 – International Space Station (internal)

Two uses are envisioned for this scenario. The first is the use of the device within a single payload to route data among various computers associated with the experiment. Similarly to scenario's 1 and 2, the ability to isolate and rate limit data traffic could be useful in mitigating problems associated with competing traffic flows. The second use is to route and isolate data among different payload racks. Current International Space Station hardware uses a payload Ethernet hub gateway (PEHG) to perform this function. In a hub configuration all payloads see each other's traffic. A router in this scenario could isolate data among different legs of the network as well as provide rate limits to avoid exceeding bandwidth limitations for downlink paths. These scenarios would not necessarily need the mobility aspect of the router for return links that go through the Tracking Data Relay Satellite System (TDRSS) network. However, if a direct to ground option was available, the mobility aspect could potentially be used. The operating conditions would be a pressurized environment internal to the Space Station allowing for air-cooling or cold plate cooling through rack cooling loops. There are special considerations for air-cooling, which have limitations on fan noise as well as how much heat can be transferred into the crew volume.

Scenario 4/5 – Lunar Orbit Communications Satellite

A lunar relay communications satellite could be required to communicate with multiple lunar surface assets in addition to Earth. Data transmission from one lunar surface asset to another, or from a surface asset to Earth could be established through the relay satellite. A

mobile router device onboard the lunar relay satellite could potentially be used to direct the data to the appropriate RF device based on the destination address. The mobility aspect of the router for the lunar/earth link would have limited application due latency problems with standardized protocols (e.g. transmission control protocol) over those distances. However, mobility features could potentially be used among lunar surface assets. The operating environment would be an un-pressurized volume requiring an active or passive thermal control system.

ORBITAL PARAMETERS

Scenario 1

Scenario 1 is a 90° orbit at an apogee of 400km. The solar weather is quiet. The model assumes no shielding, case shielding will be added in later work using the MNCP package discussed earlier.

Scenario 2

Scenario 2 is a 51.6° orbit at an apogee of 450km (This is the standard ISS orbit). The solar weather is quiet. The model assumes no shielding and the location is assumed to be the ISS exposed facility. Note that the model results show a much higher flux than scenario 1; this is the result of the South Atlantic Anomaly.

Scenario 3

Scenario 3 is the same 51.6° orbit at an apogee of 450km (ISS orbit), with the solar weather quiet. The model assumes no case shielding. The location is assumed to be internal to the US-lab.

Scenario 4

Scenario 4 is a lunar orbit at an apoapsis/periapsis of 85 km. The solar weather is quiet. The model assumes no shielding.

Scenario 5

Scenario 5 is identical to scenario 4 but uses the peak flux model for solar flare activity. This model is based on the peak five-minute averaged fluxes observed on GOES in October 1989. This model is not realistic for a whole orbit transmission model, but is used in this analysis to bound worst-case limits.

SOURCES OF RADIATION

Charged particles emanate from three sources: terrestrial, solar, and galactic.

Terrestrial sources refer to those particles trapped by the earth and are generally referred to as the Van Allen Belts. The Van Allen Belts are divided into two toroidal belts, an outer belt and an inner belt. The inner belt,

discovered by Van Allen, is made up of ions from galactic sources that are trapped by the earth. The inner belt extends to about 45° north and south geomagnetic latitudes and from about 800 km to about 8000 km in altitude. The inner belt can produce a flux of ~$3x10^4$/(cm²·s) of protons > 30MeV. The second, outer belt is made up of plasma trapped by the magnetosphere. The outer belt extends to about 70° geomagnetic latitudes, north and south, and to altitudes of 130,000km. The outer belt can produce a flux of ~$1x10^7$/(cm²·s) of protons >1MeV.

The second source, solar, is divided into four major contributing parts: Solar Particle Events (Energetic Protons), Flares, Prominence Eruptions, and Coronal Mass Ejections (CME's). Solar radiation is about 88% protons, 2% electrons, and 8% alpha particles; the remainder are various heavier nuclei. Solar radiation can produce a flux of ~$2x10^{13}$/(cm²·s) of protons of ~ 20keV. Periods of solar activity can last between 10 to 100 hours and can occur two to fourteen times a year. The number of significant events is typically one to two times a year.[3][4]

The third source of radiation is Galactic. Galactic Cosmic Rays (GCR's) originate outside the solar system. GCR's are 98% atomic nuclei and 2% electrons. Of the atomic nuclei about 90% are protons. Energies range from 10^7 to 10^{19} eV with an average of about 10^{12} eV.

TYPES OF RADIATION

The types of radiation that dominate space are: protons and heavy charged particles, electrons, neutrons, and electromagnetic radiation. The following is a very brief description of each. A more detailed explanation of each can be found is NASA CR-1871 in the section titled "Effects of the Interaction of Radiation with Matter."[5]

Protons and Heavy Charged Particles

A proton is a positively charged hydrogen ion. Most of the radiation that a spacecraft encounters will be protons. Energies in space will range from 2000eV to 10^{19} eV. The primary process by which a proton imparts energy is Coulomb-force interaction with atomic electrons.

Electrons

An electron is a particle with a mass of 1/1800 that of a proton and has a negative charge. Electrons in space are primarily found in the Van Allen belts and as secondary particles that result from collisions with other charged particles.

Neutrons

Neutrons are uncharged particles whose mass is almost equal to a proton. They are typical produced by nuclear reactions, but can also be produced when alpha particles interact with light elements such as lithium.

Electromagnetic Radiation

Electromagnetic radiation is a discrete quantity of energy which travels in a straight line at the speed of light. High energy electromagnetic radiation is usually gamma rays that emanate from the nucleus of an atom.

RADIATION MODELING

Modeling the effects of radiation on matter is a complex task that requires the understanding of both the environment and the exposed material. The modeling effort must include the effects of neutrons and protons and give both the initial energy of the particles as well as the energy deposited by recoiling atoms and their directions. The physical environment, material composition, physical size, and other variables must also be included in the models. For this task MCNP[6] will be used. MCNP is a good general application particle modeling toolkit. Modeling is effective in providing absorbed dose rates, and fluence at locations within the electric circuit.

Using this data, the TID can be determined for given mission scenarios. A theoretical SEE rate can also be determined if information is known about the topology of the circuit. Analysis can also provide design criteria and recommendations for shielding and part materials.

An additional advantage of modeling is the ability to adjust shield materials and densities and model the effectiveness and the additional recoil effects.

ENVIRONMENT MODELS

Cosmic Ray Effects on Micro Electronics - 1996 Revision (CREME96) is used for creating numerical model of the ionizing radiation environment in near Earth orbits. CREME was originally developed in 1981[7] by the Naval Research Laboratory. The CREME96 update takes into account additional knowledge collected experimentally about the ionizing environment of space. CREME96 is the DOD standard for radiation environment modeling (MIL-STD-809.) CREME96 has been found to be in good agreement will measured near Earth data.[8][9] Additional updates to CREME96 include the introduction of a trapped proton model.

For clarification several items should be explained before the data is presented. The solar radiation environment is not taken into account explicitly in the

requirements. For completion a fifth scenario is added to help account for the addition of solar particles. To accomplish this AP-8, Trapped Proton Environment Model[10] is used. This report does not include the trapped electron environment which is defined in AE-8[11].

For each scenario the target material is assumed to be silicon. Each model assumes one orbit. The range of elements is assumed to be $Z \leq 28$, or all elements with an atomic number less than or equal to 28 (nickel). For most applications this is sufficient. Energetic particles with $Z > 28$ are rare and are generally negligible. If the target device has a very high SEE threshold, or if the mission scenario has a requirement for a very low SEE rate then Z will be expanded to 92. All of the results presented start at an LET of 0.1MeV. Generally LET's less than 0.1MeV are excluded because they are generally absorbed by the cover layer.

Each scenario is presented below. Using the CREME96 model described above a numerical model was generated for each scenario. Figures 1 through 5 presented is Appendix A show the relationship between flux and LET or energy for each scenario.

The left-hand plot shows the relationship between integral flux and LET. The center plot represents the relationship between the trapped proton flux and the particle energy. Scenarios 4 and 5 do not have a trapped proton flux plot. The lunar position is outside the Earth's Magnetosphere, therefore there is no significant contribution of trapped protons. The right-hand plot shows the flux of the first five elements $Z \leq 5$. Some plots do not show all five elements as the excluded elements make minimal contributions to the total flux.

	Scenarios					
	1	2	3	4	5	
Orbiting Body	Earth	Earth	Earth	Lunar	Lunar	
Apogee	400	450	450	85	85	**km**
Perigee	400	450	450	85	85	**km**
Inclination	90	51.6	51.6	0	0	**°**
Shielding	0.00	0.00	0.63	0.00	0.00	**cm**
Proton Model	AP8MIN	AP8MIN	AP8MIN	AP8MIN	AP8MIN	
Solar Weather	Quiet	Quiet	Quiet	Quiet	Peak	
Elements	≤ 28	≤ 28	≤ 28	≤ 28	≤ 28	**Z**
Min. Energy	0.1	0.1	0.1	0.1	0.1	**MeV**

Table I - Operational Scenarios

SHIELDING

Absorbed dose is a function of the material and the shielding between the electron / proton environment and the material. Doses in silicon at the center of an aluminum sphere, representative of doses to electronic devices shielded by an equivalent thickness of aluminum, are given in Figure 6. These doses are based on the proton environment presented in scenario 2 and

are given for a range of aluminum shield thicknesses. All doses are calculated from the trapped proton /electron environment using the SHIELDOSE model. The SHIELDOSE model is documented in NBS Technical Note 1116. The data shows the importance a good shielding philosophy has on the total dose.

THERMAL

This report does not explicitly deal with the thermal environment for this device. The final report will give the results from a thermal analysis that will bound the thermal environment that this unit can be operated in. The final report will also give recommendations for passive or active thermal control of the hardware based on the results of the analysis. The results of the thermal analysis will be compared against ISS and NSTS governing documents.

CONCLUSION

This preliminary report presents operational scenarios for the use of a mobile router in space applications. These operational scenarios were translated in to specific mission classes with orbital parameters to prepare environmental models. The results and background information presented here will be used along with further analysis to present a study of the effects of radiation on a specific implementation of a commercial mobile router. These efforts will be combined with the thermal assessment in future work.
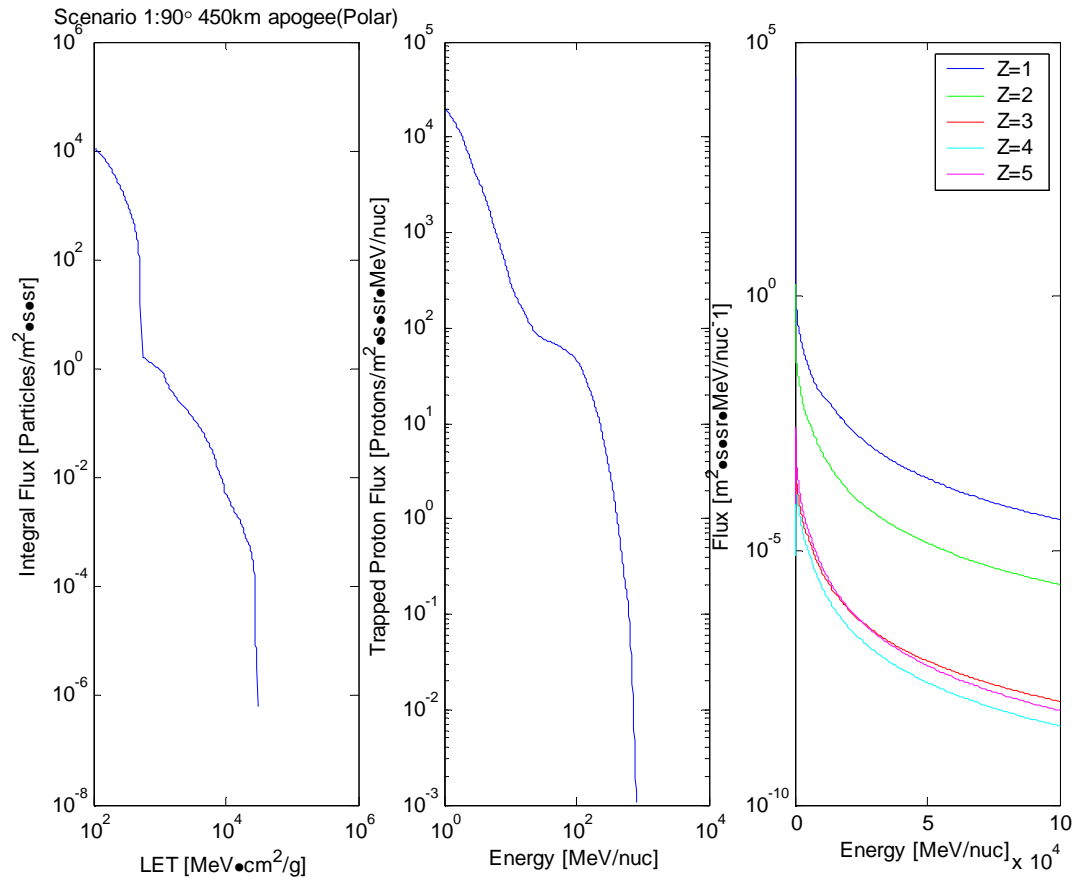
APPENDIX A – FIGURES

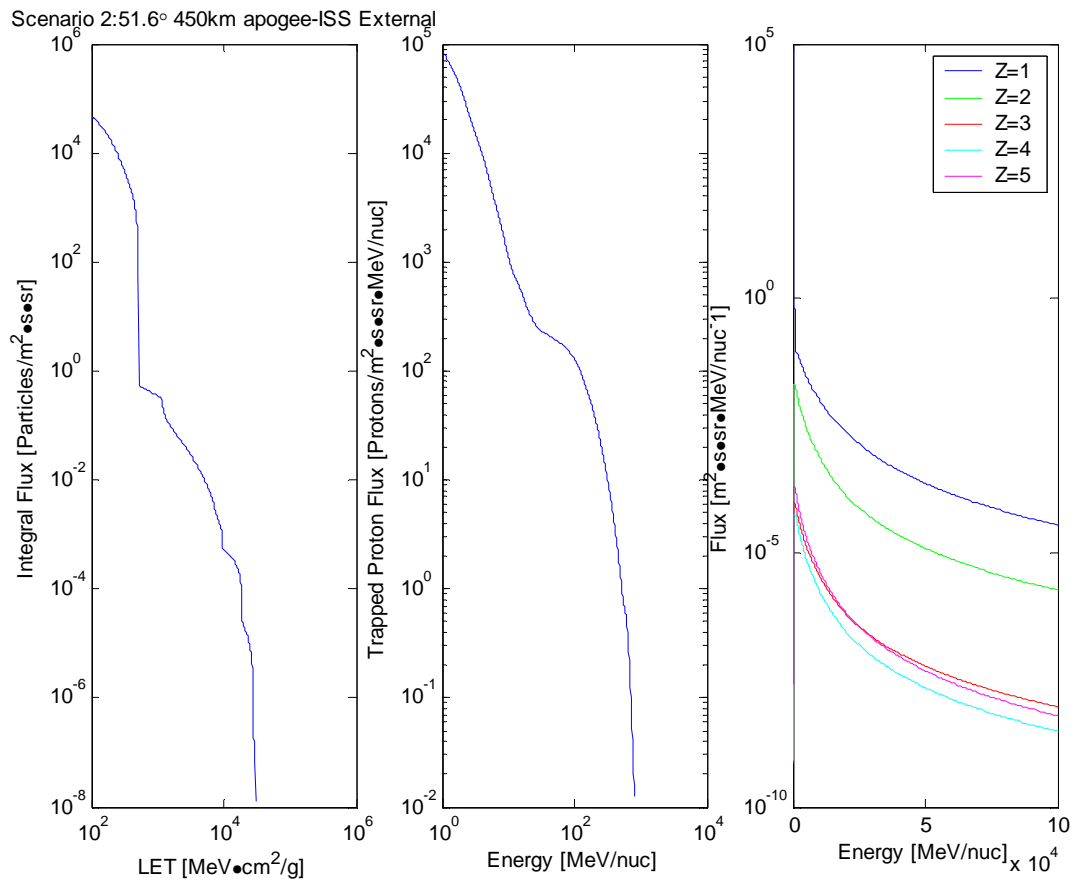**Figure 1 - Scenario 1 Environment Numerical Model**
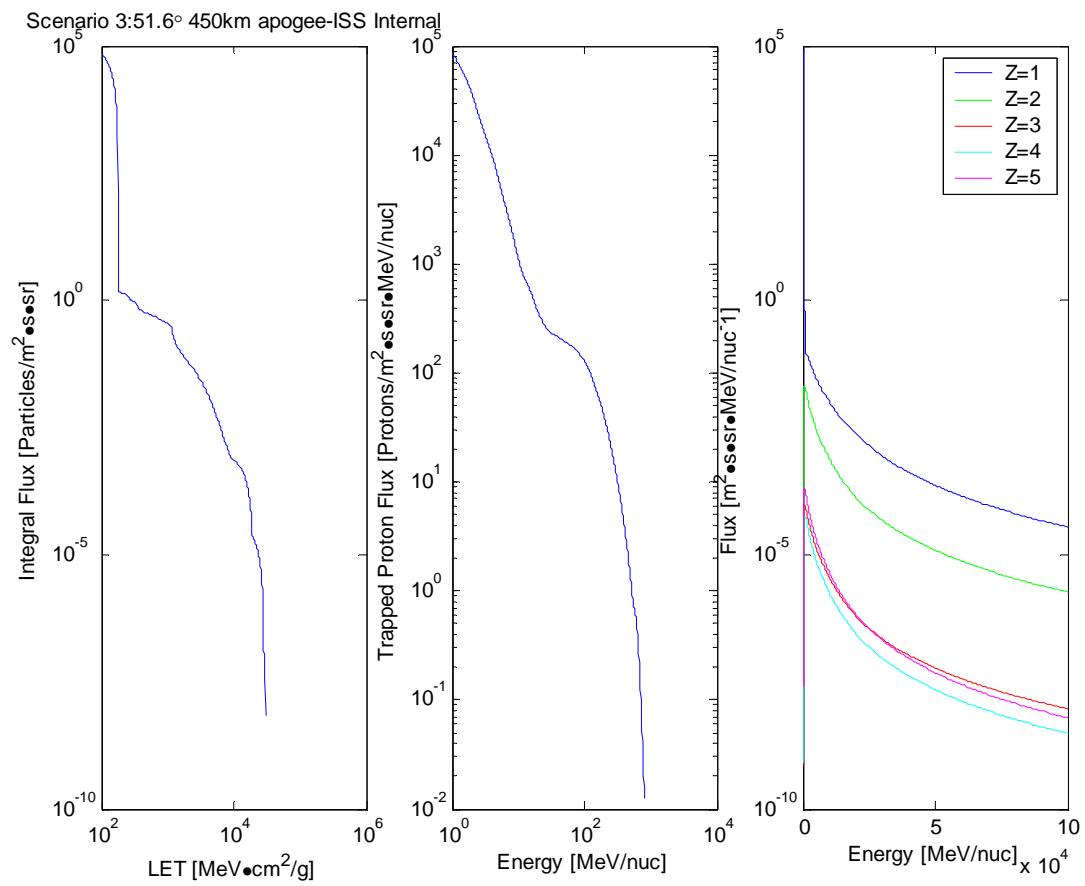
Figure 2 - Scenario 2 Environment Numerical Model

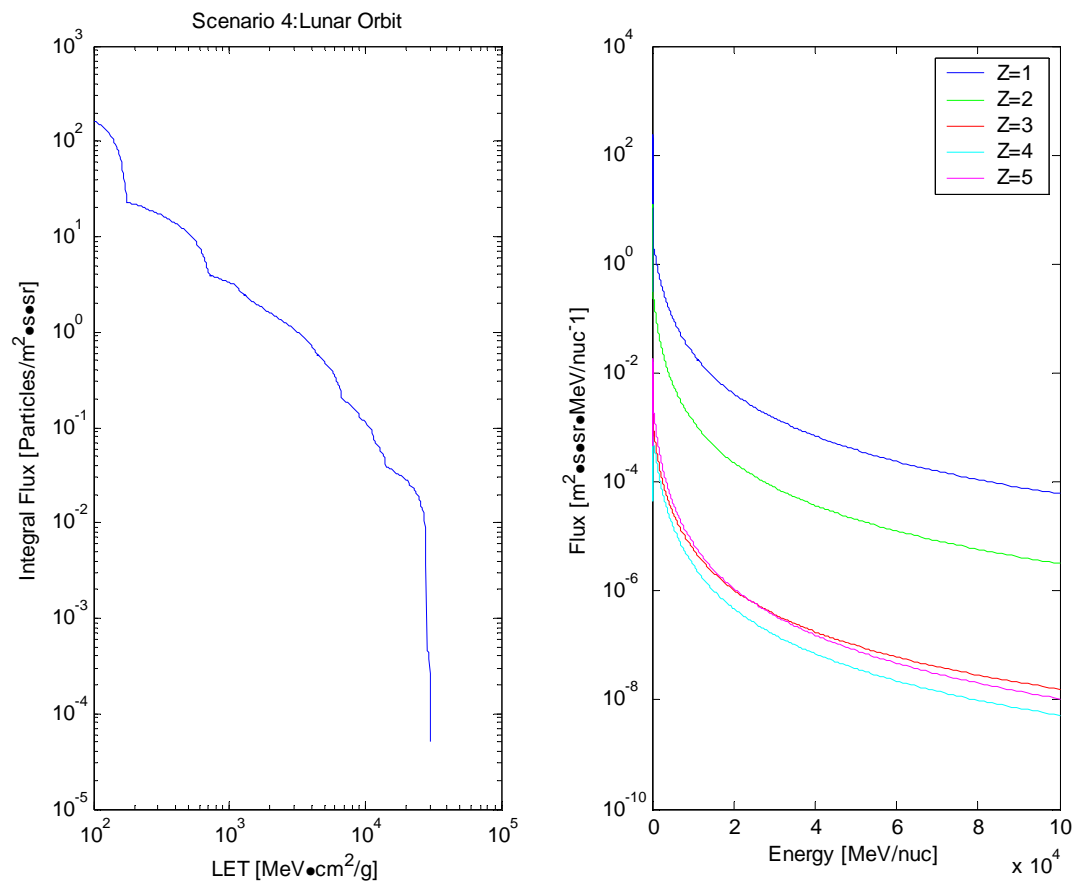**Figure 3 - Scenario 3 Environment Numerical Model**

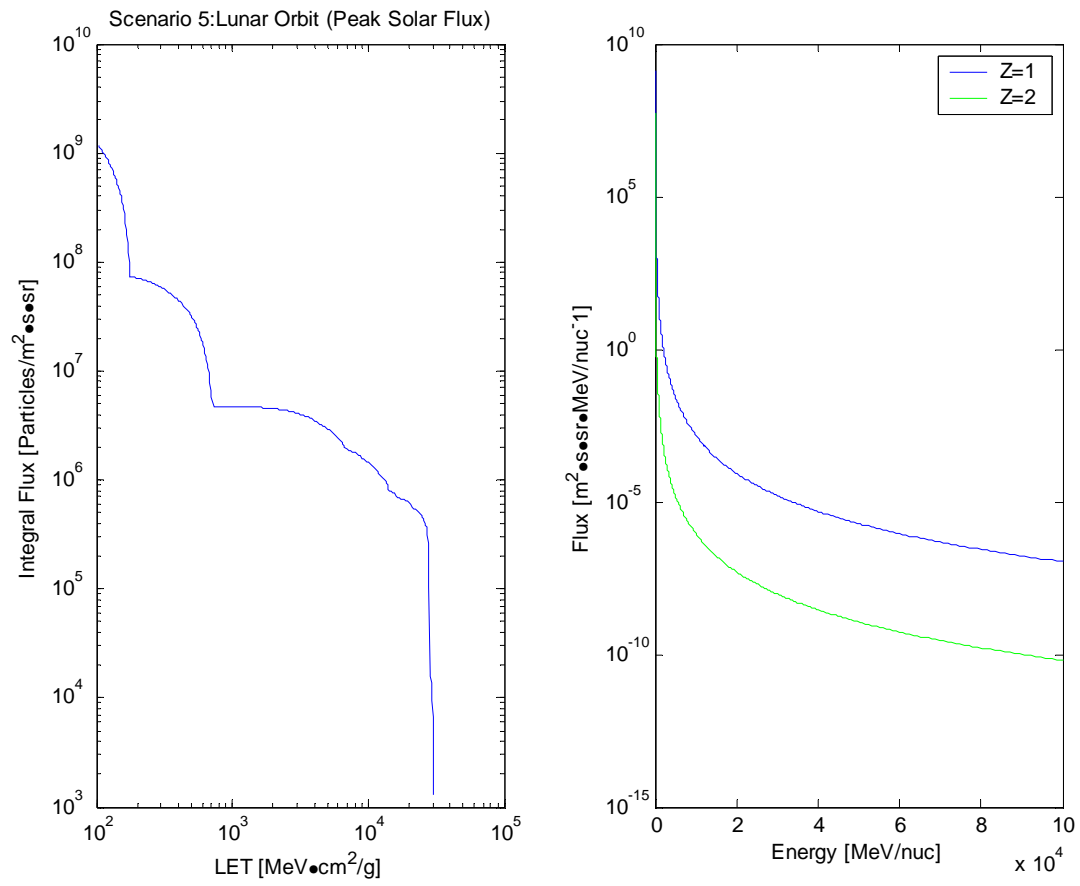**Figure 4 - Scenario 4 Environment Numerical Model**

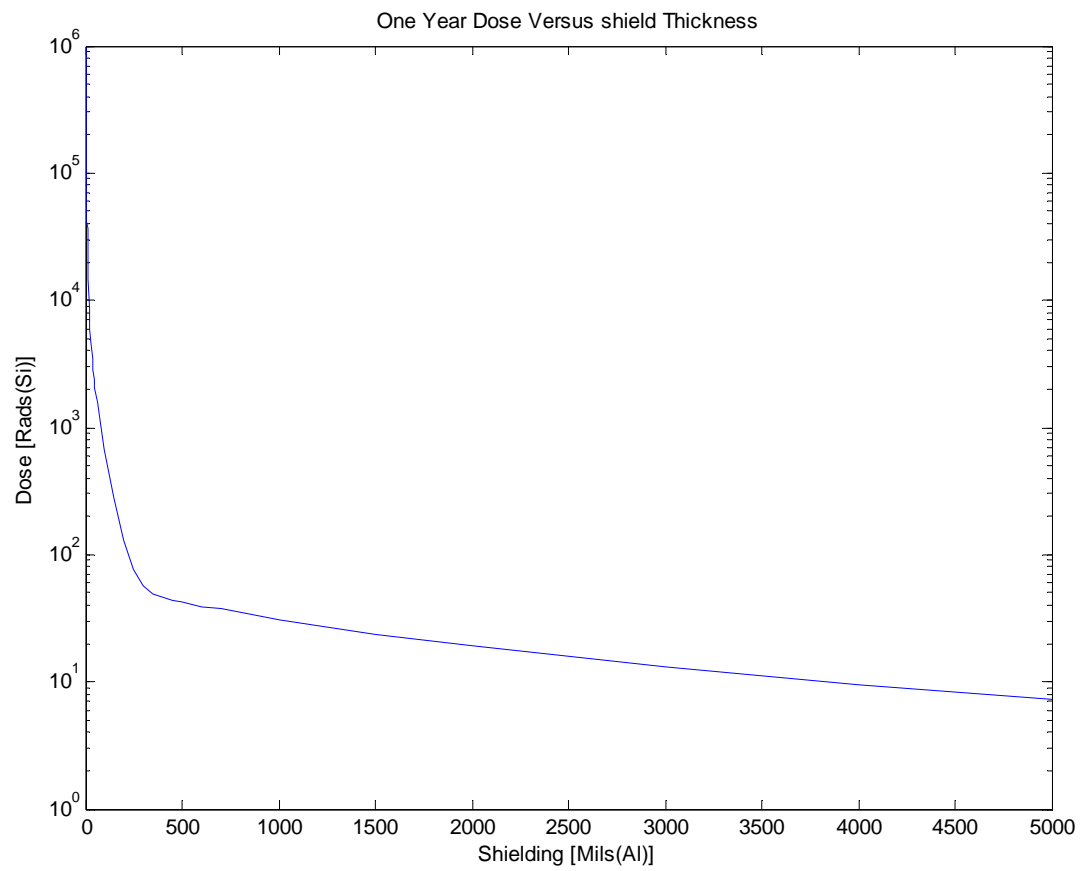**Figure 5 - Scenario 5 Environment Numerical Model**

Figure 6 - Dose versus Thickness from SHIELDOSE Model

APPENDIX B – REFERENCES

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